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Natural convection heat transfer in vertical triangular sub-channel in Zirconia-water nanofluid

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Abstract. Natural convection heat transfer in vertical triangular sub-channel has important role in cooling mechanism of the APWR and the PHWR nuclear reactors. Unfortunately, natural convection correlation equations for such geometry are scarcely available. Recent studies showed that ZrO_2-water nanofluid has a good prospect to be used in the nuclear reactor technology due to its low neutron absorption cross section. Although several papers have reported transport properties of ZrO_2-water nanofluids, practically there is no correlation equation for predicting natural convection heat transfer in a vertical triangular sub-channel in ZrO_2-water nanofluid. Therefore, a study for finding such heat transfer correlation equation has been done by utilizing Computational Fluid Dynamics software and reported in this paper. In the study, natural convection heat transfer in a vertical triangular sub-channel has been simulated at several values of heat transfer flux within 9.1 to 30.9 kW/m^2 range and ZrO_2concentrations of 0 (pure water), 0.27, and 3 volume-% of ZrO_2. The study shows that the ZrO_2 concentration has no significant influence to the natural convection heat transfer at those concentration levels. The obtained theoretical heat transfer correlation equations were verified through experiment, and they showed very similar results. The correlation equations are reported in this paper.

1. Introduction

Heat transfer fluids have many industrial and civil applications, including processes in transportation, energy supply, air-conditioning and electronic cooling, etc. Traditional base fluids, such as water, oils, glycols and fluorocarbons, have inherently relatively poor heat transfer performance due to their low values of thermal conductivities and heat capacities. Research and development activities are being carried out to improve the heat transfer properties of fluids. There are innovative ideas trying to enhance the thermal conductivity by adding solid particles of heat transport improvement agent into base fluids since Maxwell initiated it in 1881 [1]. At the very beginning, solid particles of micrometer, even millimeter magnitudes were blended into the base fluids to make suspensions. However, large

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solid particles cause troublesome problems, such as abrasion on the surface, clogging the micro channels, eroding the pipeline and increasing the pressure drop, which substantially limits the practical applications. Then, the development of nanofluid gives a new chance to overcome the problems found in conventional suspensions. Several nanoparticles that can be applied in nanofluids, such as Al_2O_3, Cu, CuO, and TiO_2 have been widely investigated. But so far nanofluid of ZrO_2-water is rarely investigated although the ZrO_2 nanofluid has a better possibility to be used in the nuclear reactor technology due to its low neutron absorption cross section [2]. Therefore, the ZrO_2-water nanofluid has been chosen as the nanofluid studied in this paper.

Meanwhile, natural convection from a bundle of hot cylinders to a cooling fluid flowing around the cylinders becomes more and more important in modern nuclear reactor applications. The heat transfer geometric configuration consisting of a bundle of cylinders and fluid among the cylinders are commonly known as a sub-channel. Unfortunately, correlation equations for predicting natural convection heat transfer in sub-channel configuration are scarcely available. Although a couple of studies have been done in seeking for such correlation equations, but the studies were limited to conventional coolants, mainly with pure water.

This paper deals with highlights of a recent research that seeks for convective heat transfer correlation equations of ZrO_2-water nanofluid as working fluid in sub-channels formed among vertical cylinders was done based on the CFD analysis. Several simulations of heat convection within a vertical sub-channel were done in the research by using commercial CFD software. The simulations were done with a various concentration of ZrO_2 in heating power levels. The results obtained form the simulation were compared to various experimental data done in the National Nuclear Energy Agency and other available data in the literature. The heat transfer correlation equations obtained in this research can be used for predicting heat transfer coefficients in sub-channels formed among vertical cylinders that are commonly utilized in nuclear reactors or heat exchangers.

2. Numerical Modeling

2.1. Geometrical model

As was mentioned in the previous section, this paper covers highlights of the theoretical study (CFD simulations) of the research that currently is being done. The main objective of the research is finding a new correlation equation for calculating natural convection heat transfer coefficient within a vertical triangular sub-channel formed among vertical cylinders to a zirconia-water nanofluid. The vertical cylinders simulate a bundle of fuel rods of a nuclear reactor or tubes of a heat exchanger. The size and geometry of vertical cylinders used in the current research specifically replicate the size of fuel rods in the Bandung TRIGA 2000 reactor of the National Nuclear Energy Agency, Indonesia.

A sketch of important parts of the test section used in the experimental part of this research is shown in figure 1.a. The experiment test section consists of a test section outer box made of glass sheets so that they are transparent, a main test section that confines a test cylinder assembly, and a distributor plate. The test cylinder assembly consists of three main (heated) cylinders and three dummy (unheated) cylinders that arranged to form triangular sub-channels. The main cylinders are equipped with electric heaters, while the dummy cylinders do not have heaters. The dummy cylinders are installed to generate similar flow pattern as that of sub-channel surrounded by a very large number of cylinders. Each main cylinder equipped with four thermocouple junctions uniformly installed along heated part of the test cylinder and one thermocouple junction installed in the unheated part of the cylinder to measure wall temperature distribution along the main cylinder length.

During the experiment, fresh water or ZrO_2-water nanofluid enters the space between the test section outer box and the main test section through a test section main inlet that is available at the bottom of the test section outer box. Most of the cooling water or ZrO_2-water nanofluid flows upward through the test section annular between the test section outer box and the main test section and leaves the test section at the main outlet. Meanwhile, a part of cooling fluid leaves the test section annular and enters the lower part of the main test section through entrance holes that are available at the lower

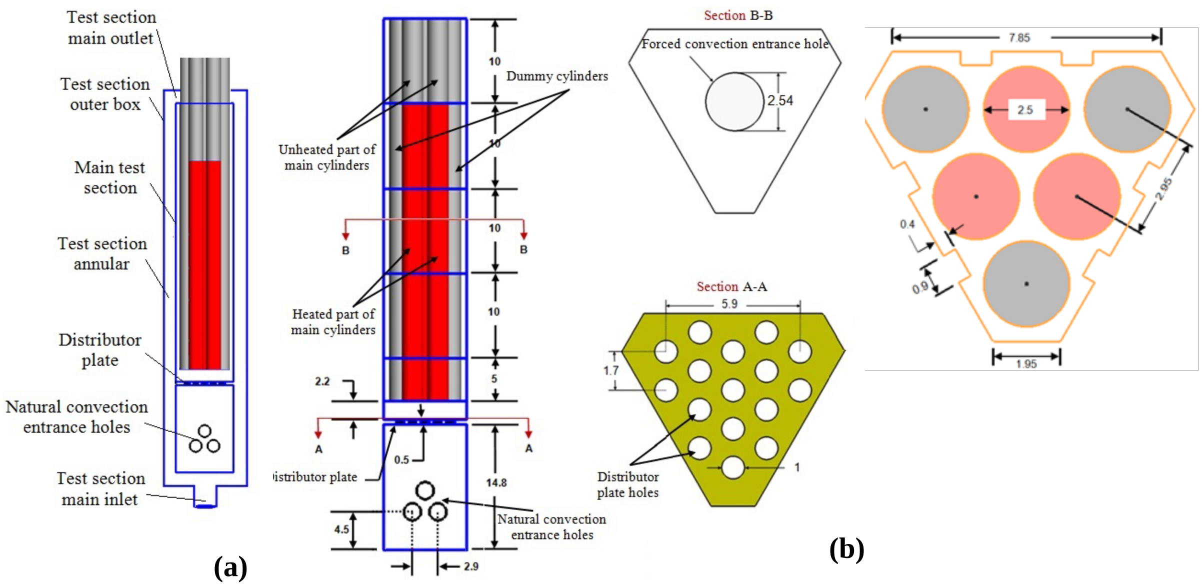


Figure 1. (a) Important parts of the experimental test section, and (b) sketch of geometrical model for the CFD simulation. All dimensions are in cm.

part of main test section walls. The cooling fluid then flows through the distributor plate that distributes the flow at the upstream end of the cylinder assembly.

A geometrical model utilized in the CFD simulation in this study is shown in figure 1.b. The calculation domain for the CFD analysis only covers the volume inside the main test section, excluding volumes of the main and dummy cylinders. As simplification, the domain around the cylinder assembly is divided into several sub domains as shown in figure 1.b, so that average temperature inside the sub-channel and average temperature on the main cylinder wall inside each sub-domain can be compared to their associated measured temperatures.

2.2. Operating condition, assumptions and governing equations

The operating condition considered in this study follows the operating condition of the experimental test of the research. During the experiment, the heater power on each cylinder varies between 250 and 850 W, which are associated to heat fluxes of 9.1 and 30.9 kW/m^2, respectively. It is assumed that the heat flux is constant and uniform over the cylinder surfaces. To observe the influence of nanoparticle concentration, there are three values of ZrO_2 volumetric concentration are simulated in the research, i.e. 0% (pure water), 0.027%, and 3%. Unfortunately, due to a limitation in the amount of available ZrO_2 nanoparticles the experiment with ZrO_2 concentration of 3% has not been done.

Several important assumptions are considered in this study and some of them are also used as boundary conditions for the CFD analysis. These assumptions are:

- The nanoparticles can be easily fluidized in the base fluid, thus, the nanofluid mixture is considered as a single phase.
- The nanoparticles and the base fluid are in thermal equilibrium with each other.
- The calculation assumes a steady operating condition.
- Pressure based computational scheme is used for the whole fluid domain.
- Since the outer box is excluded from the calculation domain, therefore the pressure at the outlet water surface is constant at the atmospheric pressure, while pressures at domain inlet are at their respective hydrostatic pressures.
- The effective thermo-physical properties of the ZrO_2-water nanofluid depend on the temperature and volume concentration of the nanoparticles and their values are obtained from literature [3]. Since the data in the literature [3] are obtained from experiments, therefore

influences of important phenomena exist in the nanofluids, e.g.: thermophoresis and the Brownian motion effects, have been reflected in the thermo-physical properties data.

- The nanofluid flow is expected to be relatively slow and the gaps between wall and cylinder surfaces are small, therefore it is assumed that the flow is laminar.
- Since the water velocity is low, therefore the viscous dissipation effect is negligible.
- No-slip condition occurs at boundaries between the cooling fluid and solid surfaces, i.e.: cylinder walls, test section walls, distributor plate, etc.
- All boundaries between the cooling fluid and solid surfaces are adiabatic, except on the heated area of the main cylinders where there are constant and uniform heat transfer fluxes.

Basically the governing equations consist of continuity equation, momentum equation, energy equation implemented in the Ansys Fluent 15.0. These equations can be expressed as following [4].

Continuity equation. The continuity equation, or equation for conservation of mass, can be written in the tensor notation as follows:

$$\nabla \cdot \left(\rho \vec{v}\right) = 0 \tag{1}$$

where ρ is the fluid mass density and $\vec{v}$ fluid velocity vector.

Momentum equation. Conservation of momentum in an inertial (non-accelerating) reference frame can be described by the following equation:

$$\nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla p + \nabla \cdot \vec{\vec{\tau}} + \rho \vec{g} \tag{2}$$

where p is the static pressure, $\vec{\vec{\tau}}$ is the stress tensor (described below), and $\rho \vec{g}$ is the gravitational body force. The stress tensor can be expressed as following:

$$\vec{\vec{\tau}} = -\mu\left[\left(\nabla \vec{v} + \nabla \vec{v}^{T}\right) - \tfrac{2}{3}\nabla \cdot \vec{v}\vec{\vec{I}}\right] \tag{3}$$

where μ is the molecular viscosity, $\vec{\vec{I}}$ is the unit tensor, and the second term on the right hand side of equation (3) represents the effect of volume dilation.

Energy equation. The energy conservation equation can be expressed in the following form:

$$\nabla \cdot \left[\vec{v}\rho\left(h + \tfrac{1}{2}v^{2}\right)\right] = \nabla \cdot \left(k \nabla T\right) \tag{4}$$

where k is the thermal conductivity of the fluid, and T is temperature of the fluid.

3. Physical properties of nanofluid

Due to the idea of dispersing solid particles of zirconia in water base fluid is newly discovered, there is no significant study about physical properties of ZrO_2-water nanofluid found in literature. The physical properties of nanofluid used in this study were based on the properties suggested by Williams et al. [5] and modified by Rea et al. [3]. Basically physical properties of the ZrO_2-water nanofluid, such as its mass density, heat capacity, viscosity, and thermal conductivity are influenced by the ZrO_2 nanoparticle volumetric concentration and the nanofluid temperature. Detailed information related to these physical properties is beyond the coverage of this paper.

4. Results and discussion

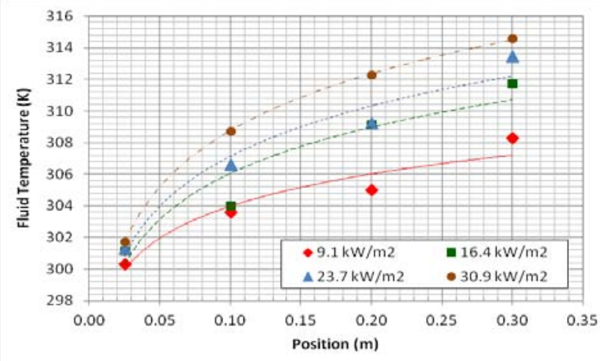
4.1. Temperature distribution

Typical distribution of fluid and cylinder surface temperature along the main cylinder length at various heat flux values are shown in figure 2. The data in figure 2 are obtained from the CFD simulations with ZrO_2-water nanofluid at solid volumetric concentration of 0.027%. CFD simulations at other nanofluid concentrations also gave very similar results as those are shown in figure 2. The position shown in figure 2 is measured in vertical direction from the lower end of the main cylinder.

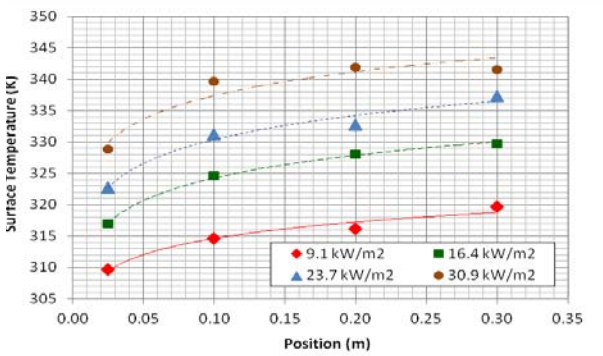
Figure 2.a shows that the fluid temperature distribution curves have relatively larger slopes near the upstream end of the cylinder compared to those at more downstream position, although theoretically slope of the fluid temperature distribution curve has to be linear if the heat flux is constant. This

relatively larger fluid temperature distribution slope suggests that there is *entrainment* or lateral flow near the upstream end of the main sub-channel, i.e. sub-channel between three main cylinders. At further downstream locations the entrainment becomes less significant so that the fluid temperature slope practically is constant. As what is generally expected, the fluid temperature distribution curves also show that the fluid temperature curve is steeper at higher heat flux.

Figure 2.b shows the cylinder surface temperature distribution along the cylinder axial position at several heat flux values. The surface temperature distribution shows similar tendency as that of the fluid temperature distribution due to previously discussed reasoning. The variation of surface temperature slope also related to the developing flow condition, i.e. the flow has not been fully developed, when its flow boundary layer thickness increases with increasing elevation.



(a)



(b)

Figure 2. Temperature distribution along the cylinder length at various heat flux values. (a) Fluid temperature. (b) Cylinder surface temperature.

4.2. Natural convective correlation equations

The postprocessor of the CFD software used in this study can evaluate area-weighted average heat transfer coefficient and mass-weighted average temperature. The obtained area-weighted average heat transfer coefficient is needed for evaluating Nusselt number *Nu*, while the mass-weighted average temperature is used for evaluating the cooling fluid physical properties needed for calculating other dimensionless parameters commonly used in natural convective correlation equations, such as Grashof number *Gr* and Rayleigh number *Ra*.

The CFD simulation results can be presented in terms of dimensionless parameters and plotted as shown in figure 3. The figure compares the natural convective correlation equations at various values of ZrO_2 volumetric concentrations obtained from the CFD simulation and their corresponding experimental data. The figure shows that the convective characteristics of these ZrO_2-water nanofluids are not significantly influenced by ZrO_2 concentration. All CFD simulation regression lines are practically the same, while the discrepancies between experimental regression lines are insignificant since they are in the same order as the data spread. The regression lines can be expressed as general equation (5) with a, b, and c values are given in table 1. The experimental Nusselt numbers in figure 3 are significantly larger than the CFD simulation Nusselt number, since the calculation domain used in the CFD simulation excludes the fluid outside the main test section so that influences of the pressure drop inside the test section annular between the inlet and outlet of the main test section was neglected (i.e. the chimney effect along the main test section was neglected in the CFD simulation), which leads to smaller pressure difference between the inlet and outlet of the test section and slower simulated fluid flow inside the main test section.

$$\lg Nu = a \lg\left(Ra \frac{D_h}{Y} \right) + b \quad \text{or} \quad Nu = c \left(Ra \frac{D_h}{Y} \right)^a \tag{5}$$

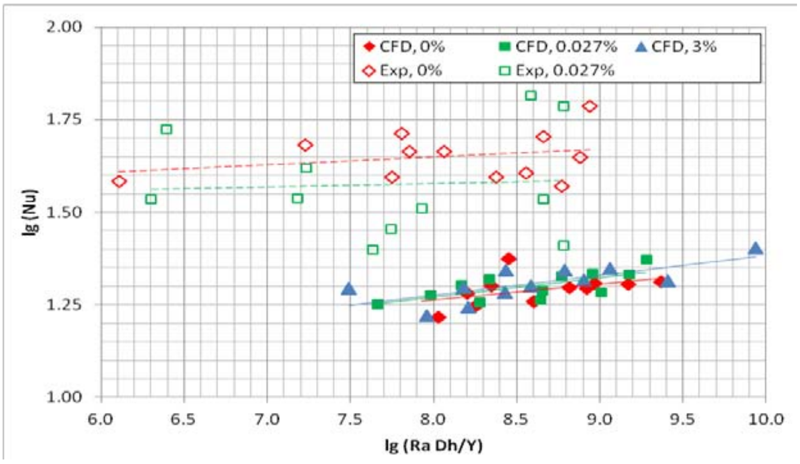


Figure 3. Natural convective correlation curves.

Table 1. Coefficients for the natural convective correlation equation.

No.	Natural Convection Case	*a*	*b*	*c*
1	CFD simulation, ZrO_2-H_2O 0% (pure H_2O)	0.042	0.927	8.445
2	CFD simulation, ZrO_2-H_2O 0.027%	0.053	0.850	7.075
3	CFD simulation, ZrO_2-H_2O 3%	0.054	0.844	6.981
4	Experiment, ZrO_2-H_2O 0% (pure water)	0.022	1.477	29.992
5	Experiment, ZrO_2-H_2O 0.027%	0.009	1.505	31.982

5. Closing Remarks

The theoretical study covered in this paper is associated to a more detailed experimental study that is still being conducted. Several natural convective correlation equations for various concentration of ZrO_2 have been obtained from the study. Both the theoretical and experimental data show that the concentration of ZrO_2 has insignificant influence to natural convection Nusselt number, for the ZrO_2 concentration is less than 3%. The correlation equations can be used for predicting the natural convection heat transfer in sub channel in ZrO_2-water nanofluids with similar geometry.

6. Acknowledgement

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7. References

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